PB-217 935

A MATHEMATICAL MODEL FOR THE POTOMAC RIVER. WHAT IT HAS DONE AND WHAT IT CAN DO. TALK PRESENTED AT THE 1966 FALL MEETING OF THE INTERSTATE COMMISSION ON THE POTOMAC RIVER BASIN, HELD AT ST. MARY'S CITY, MARYLAND, ON SEPTEMBER 22, 1966

Federal Water Pollution Control Administration
Charlottesville, Virginia

1966

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A MATHEMATICAL MODEL FOR THE POTOMAC RIVER--

WHAT IT HAS DONE AND WHAT IT CAN DO

Talk Presented at the 1966 Fall Meeting
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Interstate Commission on the Potomac River Basin
St. Mary's City, Maryland
September 22, 1966

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A MATHEMATICAL MODEL FOR THE POTOMAC RIVER--
WHAT IT HAS DONE AND WHAT IT CAN DO

"In a comprehensive water pollution program it is not sufficient to know what the existing situation is. To operate rationally and efficiently the program must be able to forecast water quality and predict what will happen if waste loads are changed or other control measures are taken."[1] The most significant area within the Chesapeake Bay-Susquehanna River Basins Project study area is probably the Potomac estuary in the Washington Metropolitan Area.

To satisfy this need for prediction capability, it was necessary to develop a mathematical model capable of simulating water quality in the Potomac River estuary.

Several models capable of simulating water quality in an estuary have been developed. After detailed investigation of the models available, the segmented estuary model developed by Dr. Robert Thomann while he was employed by the Federal Water Pollution Control Administration at the Delaware Estuary Comprehensive Project was selected as the one which most nearly conformed to the requirements of the Project. The model is highly flexible, capable of being utilized to describe any conservative or nonconservative substance. Solutions are available for both transient and steady state conditions. Its accuracy is sufficient for engineering design purposes.

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[1] Coulter, James B. "What Is A Comprehensive Water Pollution Control Program?" Journal Water Pollution Control Federation, Vol. 38, No. 6, pp. 1011-1022, June 1966.

Wait a minute. What am I talking about--mathematical models, simulation, conservative, nonconservative, steady state, transient, engineering design . .

This technical jargon of a new breed of engineers now stands in the way of the use of many new techniques which make us capable of better design and operation of the huge public facilities now considered as necessary to control water quality.

What I would like to do here is to describe in simple, understandable terms what a mathematical model for prediction of water quality in the Potomac estuary means, the progress made in its development to date, and its possible future uses.

A scientific model is a representation of some subject of inquiry. In our case, it is the quality of water in the estuary. Perhaps the most vivid examples of scientific models are the physical models of river systems and estuaries constru ted and operated by the U. S. Corps of Engineers at Vicksburg, Mississippi. These are actual scale models of the estuary with every significant detail built in. With a machine capable of simulating tides and pumps discharging water into the estuary to simulate river inflow, all of the major physi al properties of the actual estuary are represented. These include such things as salinity distribution, tidal heights, and currents. With this model operating, it is possible to evaluate the effects of such physical structures as jetties and piers on currents, sediment distribution, dredging needs, etc. Since the time scale is approximately

1 to 100, it is possible to evaluate effects which would take years to occur in the estuary by operating the model for a few days.

A mathematical model is similar to the physical model in concept. But, in a mathematical model, instead of using concrete, the physical system is represented by equations which describe all of its significant details.

Anyone who has a checking account works with a mathematical model. All deposits are positives, and all withdrawals are negatives. Monthly service charges and a charge per check further completes the model. Using technical jargon we can say that the model has a lower limit (or bound--using the correct mathematical term) in that a negative balance cannot in theory exist. Knowledge of all the inputs (deposits and withdrawals), the initial conditions (original balance) and other sources and sinks (service charges), it is possible to compute the balance at any time (a transient model).

In the same way, by proper bookkeeping and a knowledge of bounds or limits, inputs, initial condition, sources and sinks, it is possible to develop a set of equations which describe water quality in the estuary. The number of computations, of course, in this system when compared with a checking account is enormous. To solve such a system would require many man-years. But, luckily, most of the computations are routine addition, subtraction, and multiplication. Within recent years digital computers have been developed which can do such routine computations in a fraction of a second.

Properly instructed (programed), the digital computer makes possible solutions of the system available in minutes.

A key step in the development of any model is its verification, i.e., to check and see if the model truly simulates water quality. This involves a comparison of measured or observed values with compared values.

A checking account is verified every so often when a statement is received from the bank. When we compare the balance in our checkbook with the balance in the bank statement, we find time after time that we made a mistake. More often than not, it is a blunder; an input (deposit or withdrawal) was forgotten, the bank service charge was changed, or perhaps even the bank made a mistake.

This is what we have been doing with the Potomac Estuary Model for the past few years. For each water quality parameter we started by writing the equations utilizing all the inputs which we felt would affect the given water quality parameter. Then, the model (equations) would be solved and compared with what is actually measured. We would find at first that the calculated values did not match the measured values. We would then search for our mistake and find that we missed an important input or that a biochemical reaction which was assumed to occur did not occur. By this process of trial and error, we have finally arrived at what we have now--a verified model.

I would like to describe a large-scale experiment which was carried out to verify the model and discuss some other verification results in order to give you a better feel for its capabilities.

Because most natural water quality parameters are involved in so many complex chemical, biochemical, and physical reactions, they do not lend themselves to a good simple test of the model. Our first serious attempt at verification was a dye diffusion study. We injected a lipstick dye (Rhodamine WT) into the river at a constant rate and measured the resultant concentrations of dye in the river. In this case, the only significant input was the dye which we pumped into the river, and we knew the rate of pumping exactly.

The dye was pumped into the river through the effluent pipes of the District of Columbia water pollution control plant just above Marbury Point (Figure 1). Figure 2 shows the resulting average dye concentration measured opposite the plant outfall. The solid center line shows the concentration of dye predicted by the model, while the other two lines represent the actual measured concentrations at high and low water. This nice matching of the observed data and calculated data did not, of course, occur on our first try with the model. Many repetitive runs of the model were required to get the match you see here. Each run required a correction of some error or a change in a coefficient in order to get closer to the measured values.

The close agreement between the measured and calculated dye concentrations found in the above experiment shows that the segmented estuary model can satisfactorily describe water quality which will result from the introduction of a simple soluble pollutant into the estuary if the correct coefficients are known.

Getting to some more complicated parameters, I would like to show our results in modeling chlorides, dissolved oxygen, and phosphorus.

Figure 3 shows the observed and calculated variation in chlorides in the estuary at Possum Point near Quantico. Chlorides enter the estuary by diffusion upstream from the bay. The rate of diffusion depends on the tidal currents and river flow. Here you can see that, during the spring months when the river flow is high and chloride concentration is low and in the late fall when the river flow is low, the concentration of chlorides rose dramatically. Figure 3 shows a good match between predicted and observed chloride values.

Dissolved oxygen (DO) is probably one of the most important parameters to know when talking about the quality of the estuary. It is also the most difficult to model, since it can enter or leave the estuary in so many different ways. Figure 4* will give you an idea of the system which involves DO concentration in an estuary.

Our results in modeling DO, however, have been very encouraging. Figure 5 shows measured and computed values of DO at Woodrow Wilson Bridge in 1965.

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* Thaddeus A. Wastler, III, Physical Science Coordinator, Chesapeake Field Station, Chesapeake Bay-Susquehanna River Basins Project, Federal Water Pollution Control Administration, U. S. Department of the Interior, Annapolis, Maryland.

One of the problems which has recently become more prominent in water quality control is algal blooms. The system which controls algal blooms in estuaries is so complex that no one has even dared to suggest that a mathematical model of it is possible. I do not think that such a model is now technologically possible; however, models of the sub-systems which affect algal blooms are possible. One of our own efforts in this direction can be seen in Figure 6. A significant factor in prediction of algal blooms is the concentration of phosphorus. This preliminary attempt to model phosphorus (as shown in Figure 6)--while not as good a match as that for DO and chlorides--shows promise. Experiments are now being carried out to refine this model.

This is where we are now. The only question that remains is--what do we use the model for? This is where you come in.

You are the people who will decide the fate of tidewater Potomac. You represent the engineers, the biologists, the planners, the heads of the leading citizens' groups who collectively influence the actions of government. What the model offers you is a method of trying ideas and learning the consequences without great economic loss.

Let us look at some examples. A frequently heard proposal is that the Washington Metropolitan Area use the estuary as a source of water supply. Another proposal is to clean up the present pollution in the upper Potomac estuary by pumping all of the waste-water from the Metropolitan Area to the Chesapeake Bay or the Atlantic Ocean. Such action would certainly drastically change the biological

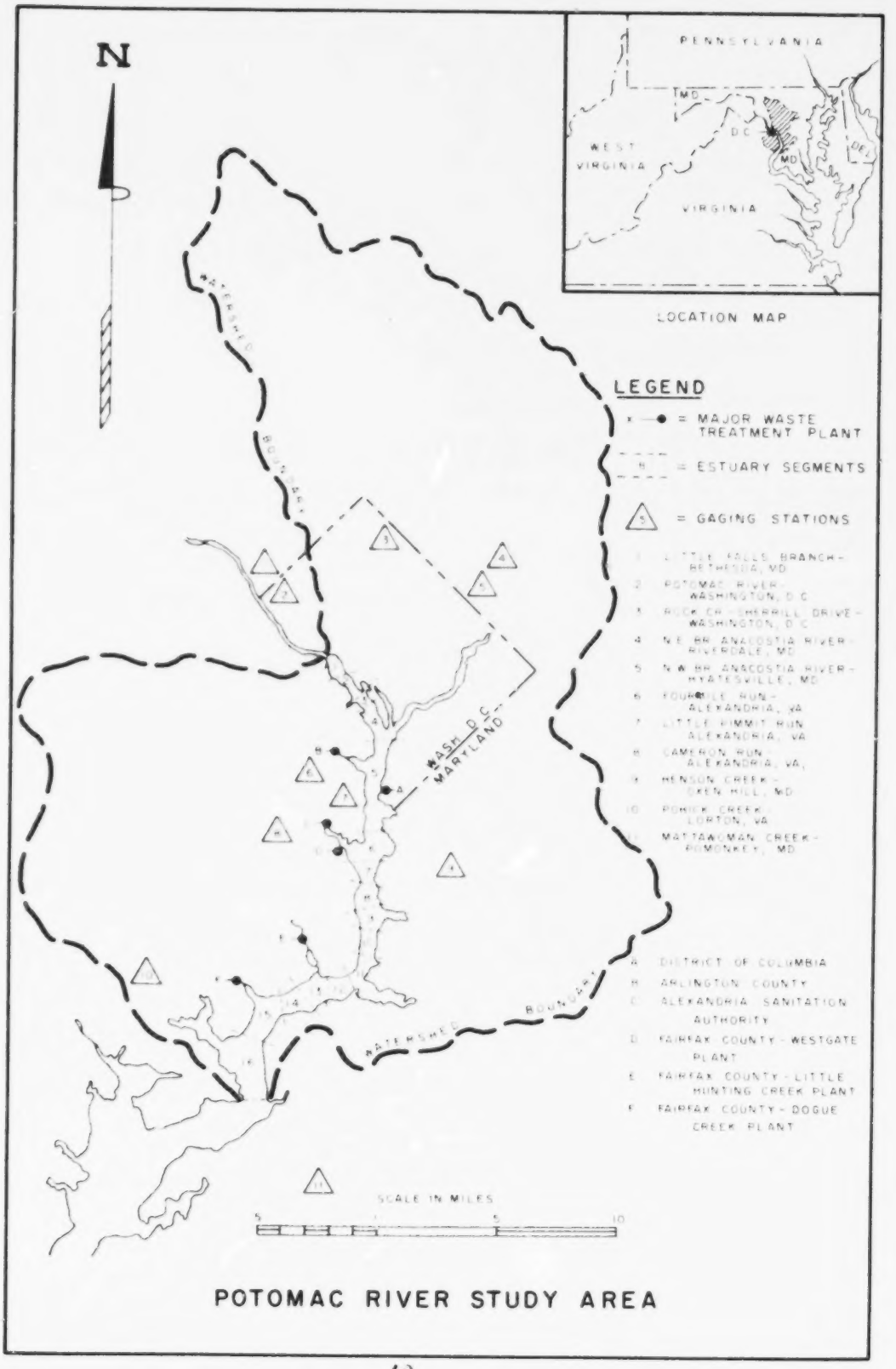
and chemical state of the estuary. One of the most significant changes would be in the concentration of chlorides (sea salts) in the estuary. The concentration of chlorides which diffuse upstream from the Chesapeake Bay is affected by the net downstream river flow. The proposed pumping of waste-waters to the Bay or the ocean would reverse the direction of flow and, in this way, significantly change the chloride concentrations. The proposal raises the following questions: Would the chloride concentrations at the head of the estuary be so high as to interfere with the use of the estuary as a water supply? What would the change in chloride concentrations do to the ecology of this portion of the estuary? Certainly the type and quantity of fish would be affected. Would there be crabs and oysters at Indian Head? Would boat owners be plagued with barnacles attaching to their craft? What would happen to the oyster industry now prospering in the lower reaches of the estuary? Certainly any dramatic changes in chlorides will affect it. These questions can be answered only if the quality of the water can be known. The mathematical model gives us a method of obtaining this knowledge.

In answer to the first question, a simulation run using the chloride model gave the results shown in Figure 7. As you can see with this figure, such a proposal would cause the chloride levels in the upper estuary to rise so high that desalinization of the upper estuary would be necessary to make it fit for drinking water. In a similar manner, the model can be used to determine the day-to-day variations in chloride concentration at any point in the estuary and,

in this way, give the engineers and scientists the necessary data to answer the above questions.

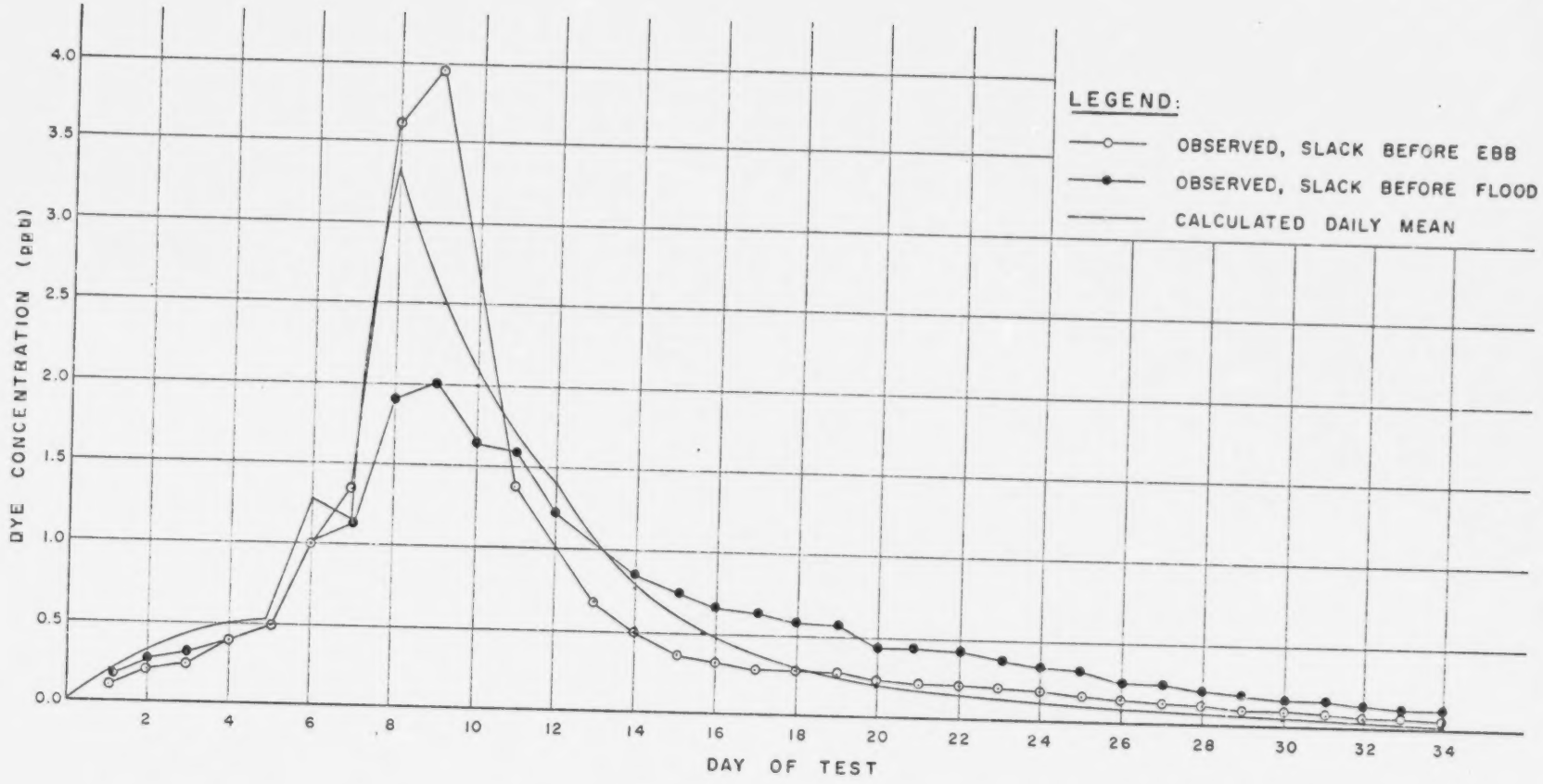
Let us look at another example. Figure 8 shows the variations in DO that can be expected at the Woodrow Wilson Bridge in 1985 under several different levels of waste-water treatment and flow. Here it is immediately evident that in 1985, if the river flow is kept at a minimum of 1,500 cfs, only 92% removal of BOD will be required at the treatment plants to maintain a minimum DO of 4 mg/l; while, if the river flow drops to 500 cfs, 95% removal of BOD will be required.

These are examples of the basic uses of the model. There are others. One of the most promising is its use in conjunction with economic techniques such as linear or dynamic programs, but that is a different story as long as the one I have just related, and I am sure that I have given you enough to absorb in one afternoon.


N
PENNSYLVANIA
MD.
D.C.
WEST VIRGINIA
MD.
VIRGINIA
DEL.
LOCATION MAP
LEGEND
= MAJOR WASTE TREATMENT PLANT
= ESTUARY SEGMENTS
= GAGING STATIONS
1 LITTLE FALLS BRANCH - BETHESDA, MD
2 POTOMAC RIVER - WASHINGTON, D.C.
3 ROCK CR. - SHERRILL DRIVE - WASHINGTON, D.C.
4 N.E. BR. ANACOSTIA RIVER - RIVERDALE, MD.
5 N.W. BR. ANACOSTIA RIVER - HYATTSVILLE, MD.
6 FOUR MILE RUN - ALEXANDRIA, VA.
7 LITTLE HIMMIT RUN ALEXANDRIA, VA.
8 CAMERON RUN - ALEXANDRIA, VA.
9 HENSON CREEK - GREEN HILL, MD.
10 POHICK CREEK - LORTON, VA.
11 MATTAWOMAN CREEK - POMONKEY, MD.
A DISTRICT OF COLUMBIA
B ARLINGTON COUNTY
C ALEXANDRIA SANITATION AUTHORITY
D FAIRFAX COUNTY - WESTGATE PLANT
E FAIRFAX COUNTY - LITTLE HUNTING CREEK PLANT
F FAIRFAX COUNTY - DOGUE CREEK PLANT
WASH. D.C. MARYLAND
WATERSHED BOUNDARY
SCALE IN MILES
5 0 5 10

POTOMAC RIVER STUDY AREA

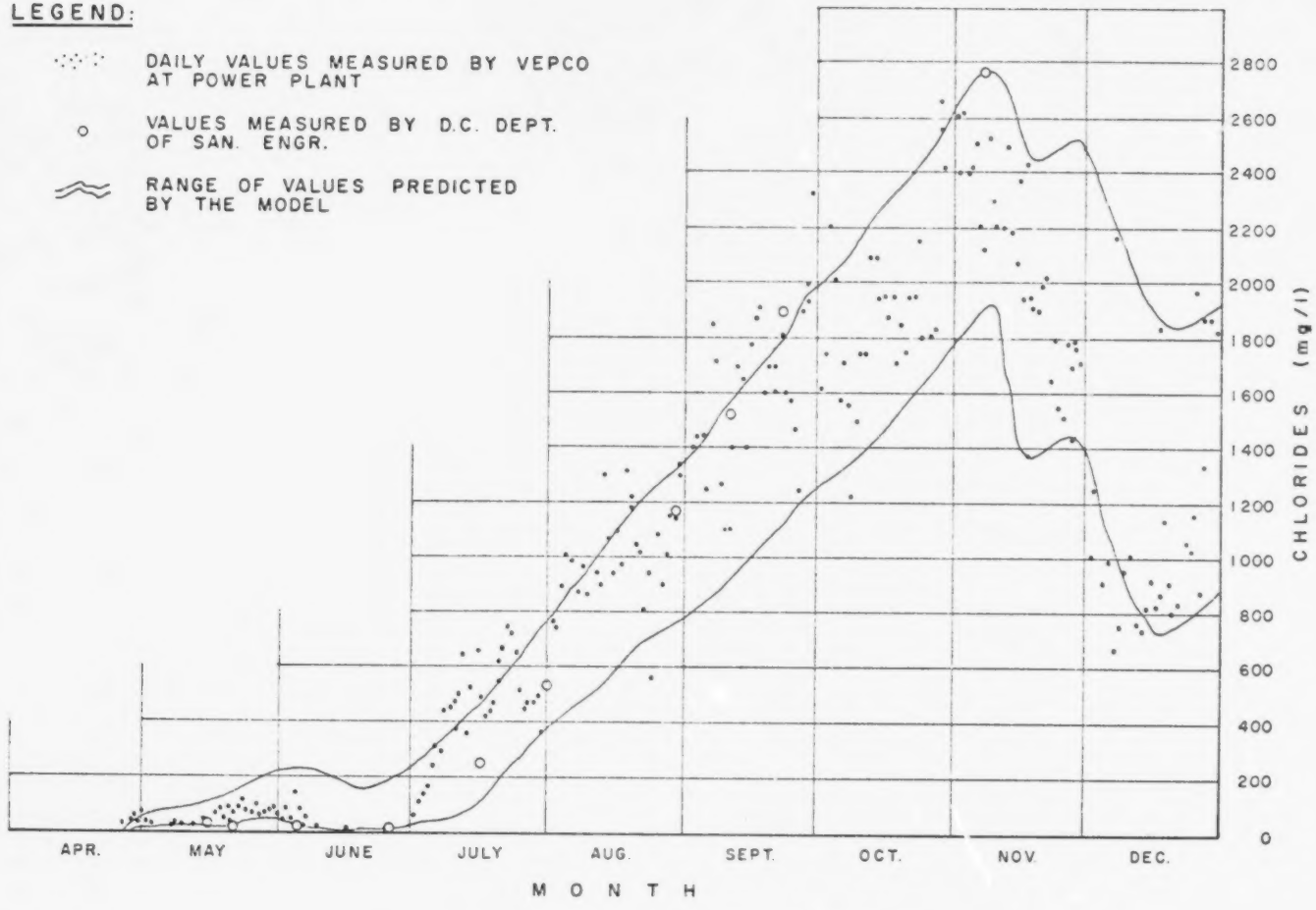
FIGURE 1



POTOMAC ESTUARY

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME

FIGURE 2



POTOMAC ESTUARY

1963 CHLORIDES AT
POSSUM POINT

FIGURE 3

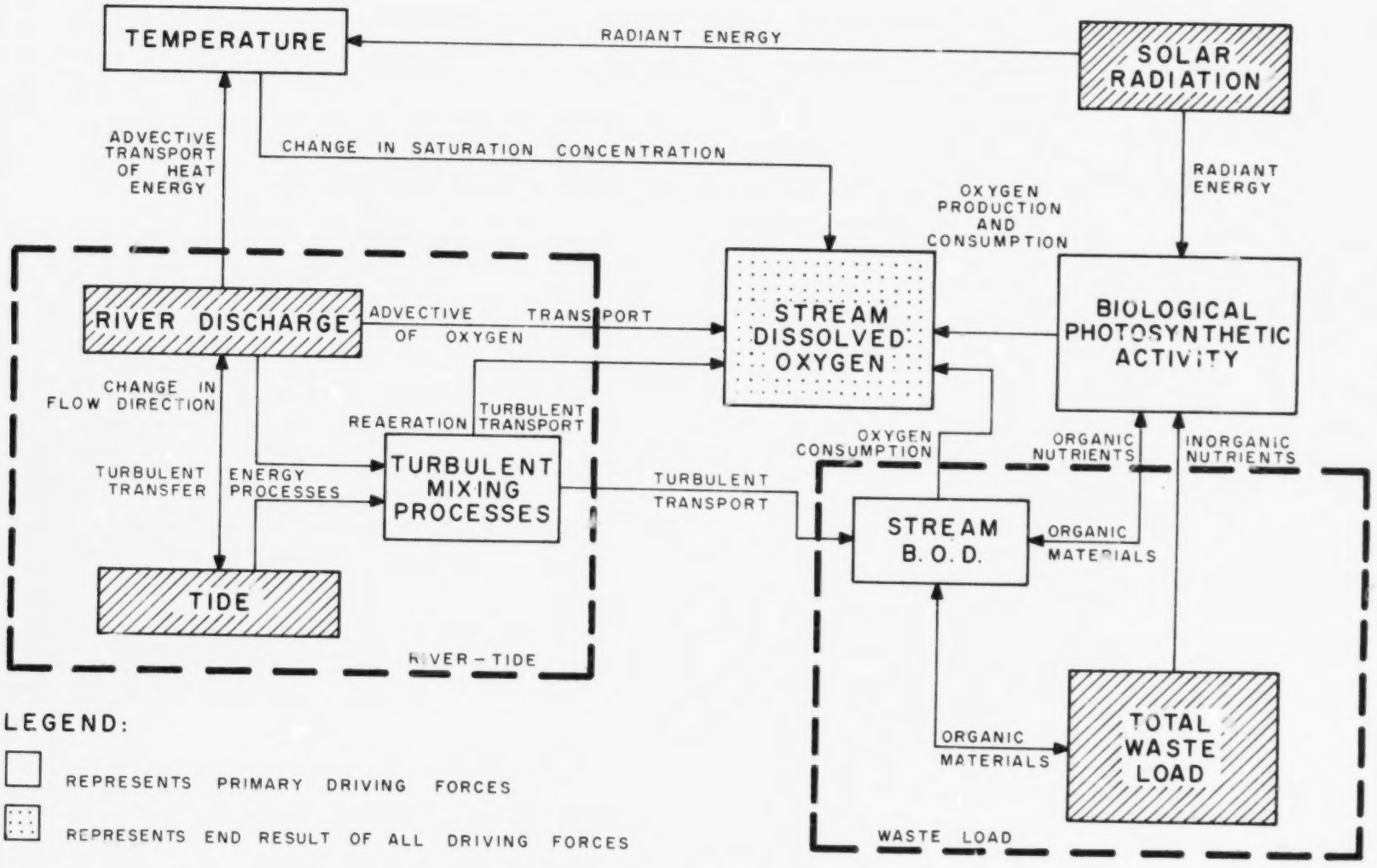
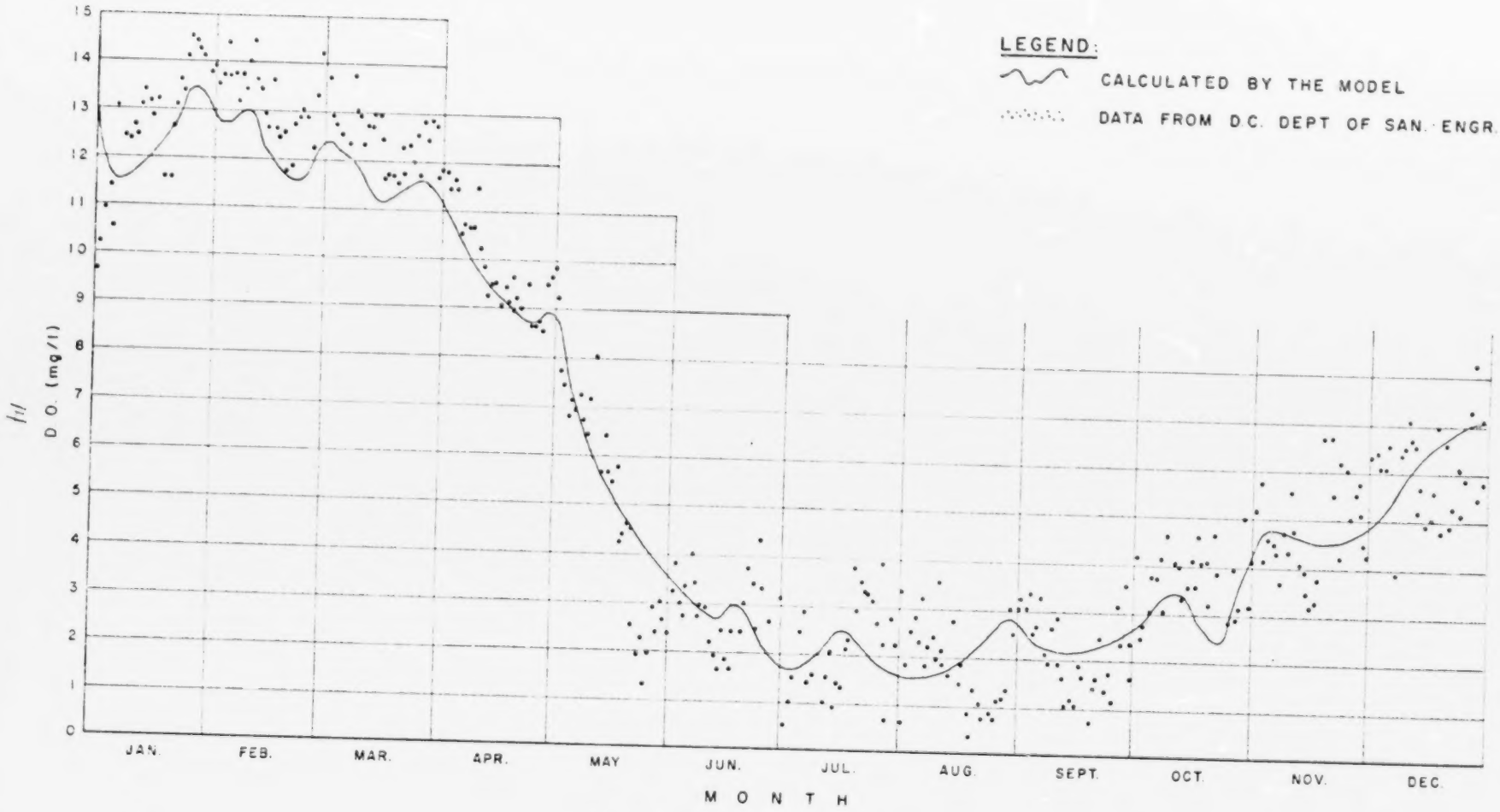


FIGURE 4

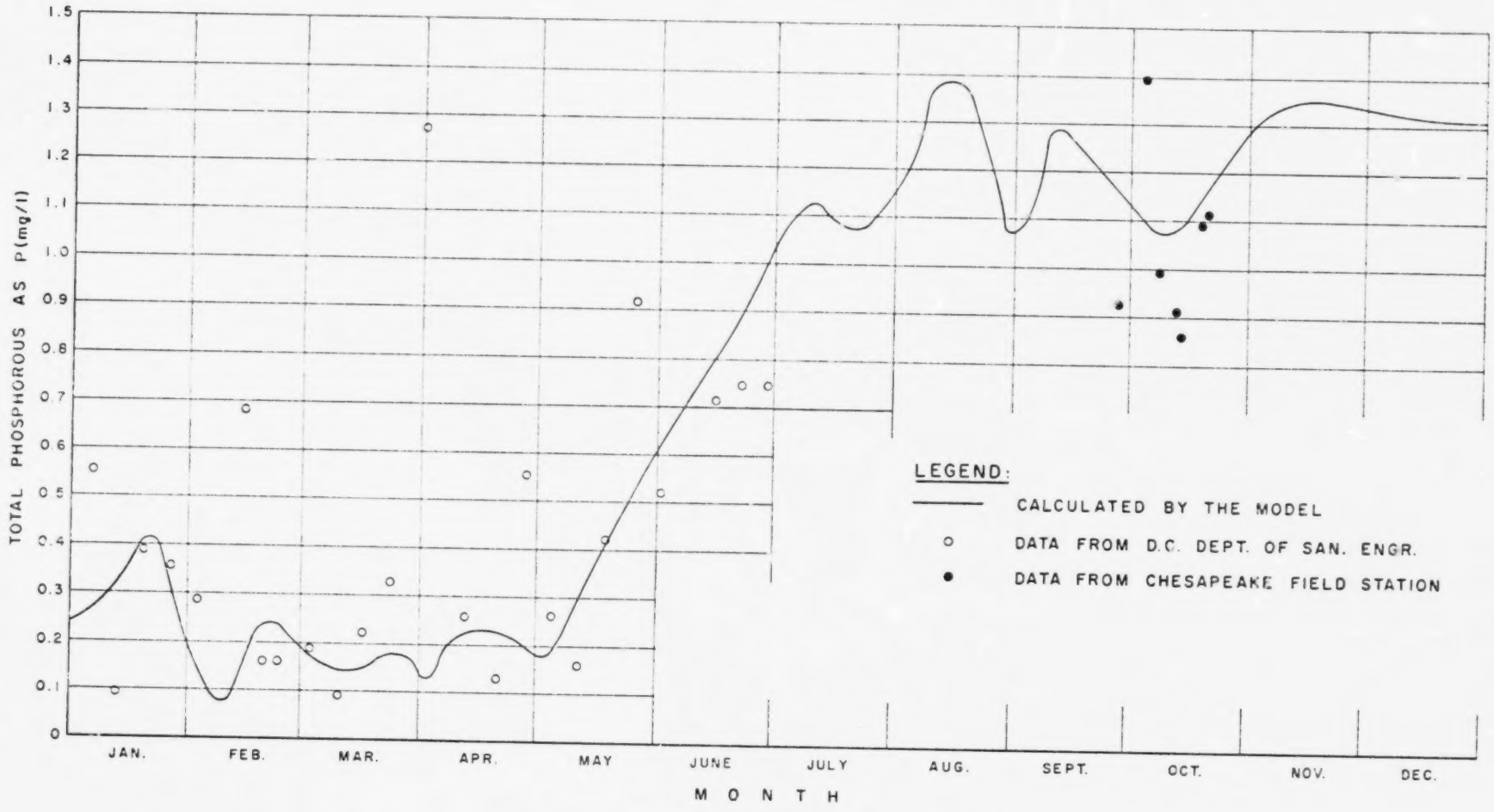
FACTORS AFFECTING STREAM DISSOLVED OXYGEN CONCENTRATION



POTOMAC ESTUARY

DISSOLVED OXYGEN CONCENTRATION AT
WOODROW WILSON BRIDGE

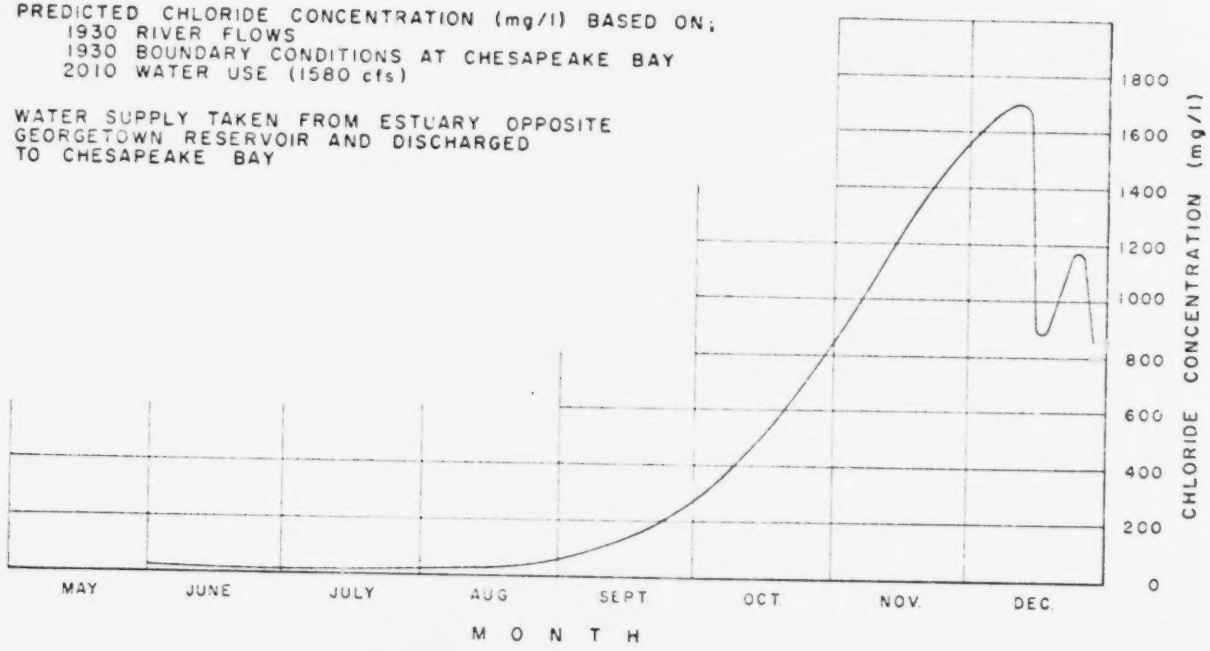
FIGURE 5



POTOMAC ESTUARY

TOTAL PHOSPHOROUS AT
WOODROW WILSON BRIDGE

FIGURE 6



POTOMAC ESTUARY

PREDICTED CHLORIDE CONCENTRATION OPPOSITE GEORGETOWN RESERVOIR

FIGURE 7

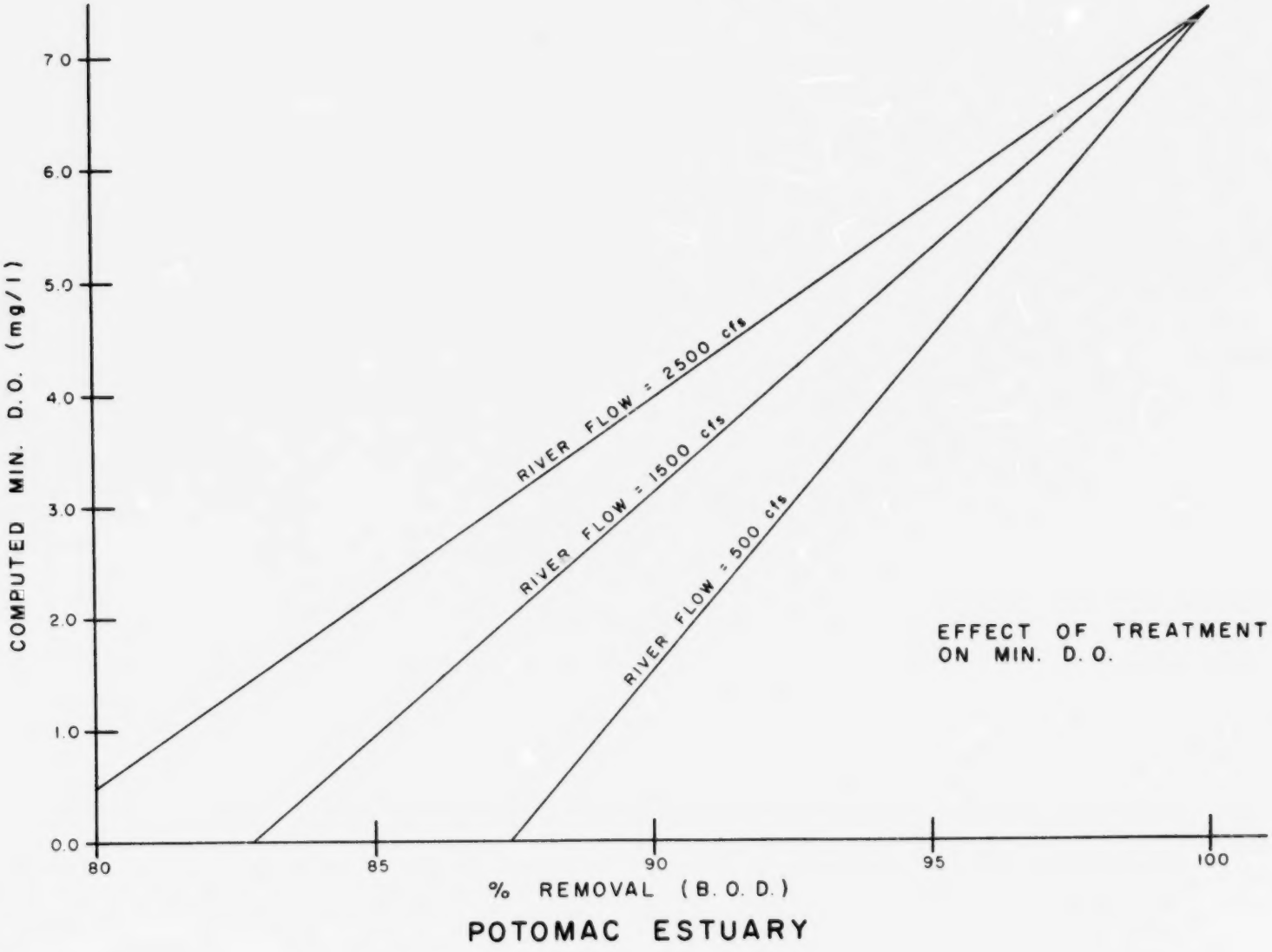

7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
COMPUTED MIN. D.O. (mg/l)
RIVER FLOW = 2500 cfs
RIVER FLOW = 1500 cfs
RIVER FLOW = 500 cfs
EFFECT OF TREATMENT
ON MIN. D.O.
80
85
90
95
100
% REMOVAL (B.O.D.)
POTOMAC ESTUARY

FIGURE 8